



U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the National Park Service

Scientific Investigations Map 3194

Geologic Map of the Cochiti Dam Quadrangle, Sandoval County, New Mexico

By David P. Dethier, Ren A. Thompson, Mark R. Hudson, Scott A. Minor, and David A. Sawyer

2011

Suggested citation:

Dethier, D.P., Thompson, R.A., Hudson, M.R., Minor, S.A., and Sawyer, D.A., 2011, Geologic map of the Cochiti Dam quadrangle, Sandoval County, New Mexico: U.S. Geological Survey Scientific Investigations Map 3194, 1 sheet, scale 1:24,000.

Denver Publishing Service Center

Edit and digital layout by L.J. Binder

Manuscript approved for publication August 31, 2011

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INTRODUCTION

The Cochiti Dam quadrangle is located in the southern part of the Española Basin (fig. 1) and contains sedimentary and volcanic deposits that record alluvial, colluvial, tectonic and volcanic processes over the past seventeen million years. The geology was mapped from 1997 to 1999 and modified from 2004 through 2008. The primary mapping responsibilities were as follows: Dethier mapped the surficial deposits, basin-fill sedimentary deposits, Miocene to Quaternary volcanic deposits of the Jemez volcanic field, and a preliminary version of fault distribution. Thompson and Hudson mapped the Pliocene and Quaternary volcanic deposits of the Cerros del Rio volcanic field. Thompson, Minor, and Hudson mapped surface exposures of faults and Hudson conducted paleomagnetic studies for stratigraphic correlations. Thompson prepared the digital compilation of the geologic map.

The mapped distribution of units is based primarily on interpretation of 1:16,000-scale, color aerial photographs taken in 1992, and 1:40,000-scale, black-and-white, aerial photographs taken in 1996 (U.S. Geological Survey National Aerial Photography Program (NAPP) available at <http://eros.usgs.gov/#/Guides/napp>). Most of the contacts on the map were transferred from the aerial photographs using a photogrammetric stereoplotter and subsequently field checked for accuracy and revised based on field determination of allostratigraphic and lithostratigraphic units. Determination of lithostratigraphic units in volcanic deposits was aided by geochemical data, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, aeromagnetic and paleomagnetic data (Grauch and Bankey, 2003; Grauch and others, 2006; Thompson and others, 2006). Supplemental revision of mapped contacts was based on interpretation of U.S. Geological Survey (USGS) 1-meter orthoimagery. This version of the Cochiti Dam quadrangle geologic map uses the USGS 1:24,000-scale Cochiti Dam, New Mexico quadrangle as the topographic base overlain on a screened shaded relief base generated from 10-m digital elevation model (DEM) data from the USGS National Elevation Dataset (NED, <http://ned.usgs.gov/>); sun illumination is from the northwest at 45° above the horizon.

For continuity, geologic units are delineated in areas now inundated by Cochiti Lake and in areas where natural topography was altered by excavation of material used in the construction of Cochiti Dam. Contacts in these areas are drawn using topography mapped in 1953, guided by aerial-photographic interpretation and mapping in adjacent areas. Northwest of the Pajarito fault zone in the northwest part of the map area, contacts and map unit descriptions were derived largely from Goff and others (1990). Major tributary canyons to the Rio Grande are labeled in figure 2 and a simplified fault diagram is shown as figure 3.

ACKNOWLEDGMENTS

The authors thank Margaret E. Berry and Florian Maldonado of the U.S. Geological Survey for their thorough reviews that greatly improved the report. V.J.S. Grauch prepared, and assisted with interpretation of, aeromagnetic data used to constrain lithostratigraphic units in the volcanic rocks. We gratefully acknowledge Daniel P. Miggins of the U.S. Geological Survey and William McIntosh of New Mexico Institute of Mining and Technology for previously unreported $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations of volcanic rocks referenced in this report.

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Table 1. Map units, eruption ages, and volcanic rock names for the Cerros del Rio volcanic field deposits.

Table 2. Locations for samples referenced in the text.

Photograph: View southwest from above the confluence of Arroyo Montoso and Rio Grande in White Rock Canyon. Photograph by Ren Thompson, 2006.

Photograph: *Yucca baccata*. Photograph by Stan Shebs, 2004. Image available at: http://upload.wikimedia.org/wikipedia/commons/9/96/Yucca_baccata_whole.jpg.

Photograph: View northwest toward mouth of Tetilla Canyon in the southeastern part of the map area. Photograph by Ren Thompson, 2006.

Photograph: Roadrunner. Image WO3862 by Gary Kramer, U.S. Fish and Wildlife Service, 2008. <http://digitalmedia.fws.gov/>.

Photograph: Rubbly base of basaltic andesite lava flow typical of flow morphology of mafic lavas exposed along La Bajada Fault. Photograph by Ren A Thompson, 2006.

Figure 1. Location map and general geology of the Española Basin, adjacent basin, and volcanic fields of the Rio Grande rift. Geology modified from Smith and others (2001, fig. 3). Approximate location of the Toledo caldera (Toledo embayment) is modified from Gardner and Goff (1996). Volcanic fields: CdRvf, Cerros del Rio volcanic field; SAMvf, Santa Ana Mesa volcanic field; TPvf, Taos Plateau volcanic field. Faults: EB, Embudo fault, JZ, Jemez fault; LB, La Bajada fault; PJ, Pajarito fault; SF, San Francisco fault.

Figure 2. Landsat 7 satellite image (30-m band 7–4–2 merged with 15-m band 8) acquired on October 14, 1999, of Cerros del Rio, New Mexico area (image clip from Sawyer and others, 2004), showing select geologic features and geographic names. Yellow rectangle is the boundary of the Cochiti Dam 7.5-minute quadrangle.

Figure 3. Landsat 7 image (30-m band 7–4–2 merged with 15-m band 8) acquired on October 14, 1999; image clip from Sawyer and others, 2004) of Cerros del Rio volcanic field showing approximate eruptive extent as purple dashed line, mapped vent areas as red stars and presumed buried vents based on aeromagnetic data as yellow stars. Geographic abbreviations: LA, Los Alamos; WR, White Rock; CL, Cochiti Lake; BM, Buckman Mesa; OM, Ortiz Mountain; MP, Montoso Peak; CM, Cerro Micho; TH, Twin Hills; CP, Cerro Portillo; CC, Cerro Colorado; CV, Cochiti Volcano; TP, Tetilla Peak; MJ, Mesita de Juana. Major mapped faults and lineaments are shown in red and aeromagnetic lineaments related to buried faults are shown in purple. Fault abbreviations: PJ, Pajarito fault; SF, San Francisco fault; LB, La Bajada fault; TT, Tetilla fault; CM, Cerro Micho fault; CC, Cerro Colorado fault; CO, Cochiti fault; TH, Twin Hills fault; CP, Cerro Portillo fault; LT, Las Tetillitas fault; AC, Arroyo Calabasas fault. Quadrangle outline in yellow.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

The surficial map units on this map are informal allostratigraphic units of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). For this reason, subdivisions of stratigraphic units use time terms “late” and “early” where applied to surficial units, but use position terms “upper” and “lower” where applied to lithostratigraphic units. The El Cajete tephra, erupted from the Jemez Mountains at ~50 to 60 ka (Reneau and others, 1996) provides an important late Pleistocene time-stratigraphic marker in much of the area. Soil development (presence and type of B horizons) and the morphologic stage of pedogenic carbonate accumulation, Stage I to Stage IV, provide another means of estimating the approximate age of Quaternary deposits in the area (Birkeland, 1999).

Artificial-Fill deposits

Af **Artificial fill (latest Holocene)**—Rock and earth fill of Cochiti Dam and associated structures

Alluvial deposits

Qaf **Fan alluvium (Holocene to middle Pleistocene)**—Cross-bedded, poorly sorted cobble to boulder gravel and poorly sorted, matrix-rich debris-flow deposits. Older deposits are preserved as remnants 5–15 m above active alluvial fans on slopes from 4° to 10°. Includes eolian deposits and local areas of ~55 ka El Cajete tephra along La Bajada fault escarpment in the southeast part of map area. Soils within deposit are poorly exposed, but locally thicker than 1 m, with Stage III

or weak Stage IV carbonate morphology. Thickness probably 4–20 m; most contacts obscured by colluvium

- Qa **Alluvium (Holocene)**—Cross- to planar-bedded sand, pebbly sand, and thin beds of silty sand exposed along the Rio Grande, along active channels of tributary arroyos, beneath adjacent low (< 3 m) terraces and on low-gradient alluvial fans at the mouths of Sanchez and Medio Canyons. Beds generally less than 0.5 m thick. Includes some late Pleistocene deposits in upland areas northeast of the Town of Cochiti Lake. Actual thickness is probably greater than 10 m along the Rio Grande. Soils thin (< 0.5 m) ranging from A/C profiles to profiles with Bw and (or) Bk horizons with Stage II carbonate morphology on low terraces. Exposed thickness 2–4 m, base not exposed
- Qa₅ **Alluvial deposit 5 (Holocene to late Pleistocene)**—Cross-to planar-bedded sand and pebbly sand, and thin beds of silty sand beneath narrow terraces 3–10 m above the Rio Grande. Beds generally <0.5 m thick. Most extensive deposits located 1 km south of Alamo Canyon. Soils thin (<0.5 m) ranging from A/C profiles to profiles with Bw and (or) Bk horizons with Stage II carbonate morphology. Exposed thickness 3–10 m, base not exposed
- Qa₄ **Alluvial deposit 4 (late Pleistocene)**—Well-sorted cobble to boulder gravel, cross-bedded sand, and thin-bedded sand of fluvial origin and fluvial and eolian silty sand beneath terrace remnants 14–20 m above the Rio Grande. Exposed mainly at mouths of tributaries such as Medio Canyon and in the southern part of the map area. Overlies Santa Fe Group deposits, landslide deposits, or older alluvium. Deposits are extensive near Cochiti Dam, where 5–10 m of axial river cobble-gravel overlies basaltic boulders and underlies piedmont alluvium mainly derived from the west. Deposits apparently lie beneath the ~55 ka El Cajete tephra. Soils <1.0 m thick and poorly exposed with Stage II or weak Stage III carbonate morphology. Thickness probably 4–20 m
- Qa₃ **Alluvial deposit 3 (middle Pleistocene)**—Well-sorted cobble to poorly sorted boulder gravel, cross-bedded sand, and thin-bedded sand beneath terrace remnants 25–45 m above the Rio Grande, preserved at mouths of tributaries and in an extensive deposit near Alamo Canyon that contain angular boulders as large as 3.5 m. Clasts are predominantly axial river lithologies but are locally rich in andesitic and dacitic rocks derived from volcanic terrane to the west. Overlies and truncates rocks of the Santa Fe Group, landslide deposits, older alluvium or hydromagmatic deposits. Extensive deposits on both sides of Rio Grande near the mouth of Alamo Canyon are overlain by El Cajete tephra. Soils 0.5–1.0 m thick contain Stage II or Stage III carbonate morphology and local buried Bt horizons. Thickness 4–15 m
- Qa₂ **Alluvial deposit 2 (middle? Pleistocene)**—Well-sorted cobble to boulder gravel containing layers composed of boulders as large as 3 m, exposed beneath terrace remnants approximately 50 to 70 m above the Rio Grande. Contact relations best exposed on both sides of Cochiti Lake, south and southwest of the Tetilla Peak overlook, where 8–25 m of gravelly axial channel deposits overlie lower Pleistocene and Pliocene cobble gravel of the Santa Fe Group; axial

facies. These deposits contain laterally extensive boulder layers. Sandy to silt rich piedmont alluvium 2–8 m thick derived from eastern sources and layers of angular boulders of basalt interfinger with and overlie the axial alluvium in the southeastern part of map area. Overlies Santa Fe Group or landslide deposits. Deposits contain clasts of upper Bandelier Tuff and a local bed of ~0.55 Ma tephra derived from Valles caldera. Amino-acid ratios from gastropods in the upper 5 m of the deposits suggest a local age of 250 to 300 ka (see Dethier and McCoy, 1993). Deposits are overlain by El Cajete tephra (~55 ka; Reneau and others, 1996) and may be in part coeval with unit Qal. Soils are 0.8–1.5 m thick and contain Stage IV carbonate in gravel; finer piedmont deposits expose several buried Bt horizons locally and carbonate development is Stage III. Thickness generally 10–30 m

- Qa₁ **Alluvial deposit 1 (early Pleistocene)**—Poorly sorted boulder gravel containing clasts of volcanic rock as large as 4 m, well-sorted cobble gravel and beds of coarse sand exposed beneath terrace remnants 80–130 m above the Rio Grande south of the mouth of Capulin Canyon. Boulder-rich beds contain abundant clasts of andesite and welded Bandelier Tuff and minor basalt or axial-river lithologies derived from sources northwest of the modern river. Most exposures contain boulders of, and are thus younger than, the 1.22 Ma Tshirege Member of the Bandelier Tuff (Izett and Obradovich, 1994); basal exposures at several sites contain no axial lithologies and fill narrow paleodrainages cut into the Tshirege Member of the Bandelier Tuff. Deposits SE of the Town of Cochiti Lake contain boulders of the 1.61 Ma Otowi Member of the Bandelier Tuff (Izett and Obradovich, 1994). Deposits overlie basaltic or andesitic rocks in most areas. Overlain by eolian deposits, El Cajete tephra, and locally derived alluvium. Soils are 1.0 to > 2.0 m thick; finer overlying piedmont deposits expose multiple buried Bt horizons locally. Carbonate development is Stage III+ or Stage IV; carbonate-rich horizons locally brecciated and broken by vertical veins. Deposits at several sites between Alamo Canyon and Sanchez Canyon fill narrow paleocanyons cut before deposition of lower Bandelier Tuff (Reneau and Dethier, 1996). Locally overlain by upper Bandelier Tuff. Thickness generally 10–30 m, but thicker near the mouth of Medio Canyon

Piedmont deposits

- Qp₅ **Piedmont alluvial deposit 5 (Holocene to late Pleistocene)**—Cross-to planar-bedded sand and pebbly sand and poorly sorted gravel. Clasts predominantly andesite and silicic tuff derived from the Jemez Mountains to the west; matrix rich in lithic fragments and quartz. Deposits 0.5– 4.0 m thick are exposed beneath terraces 3–10 m above Rio Chiquito and adjacent tributaries graded to the Rio Grande. Beds generally <0.5 m thick. Soils are thin (<0.5 m) ranging from A/C profiles to profiles with Bw and (or) Bk horizons with Stage II carbonate. Exposed thickness 3–10 m, base not exposed
- Qp₄ **Piedmont alluvial deposit 4 (late Pleistocene)**—Poorly sorted cobble to boulder gravel, sand, and local silty sand. West of the Rio Grande, clasts are predominantly andesite and silicic tuff derived from the Jemez Mountains to the west and the matrix is rich in lithic fragments and

quartz. To the east, granitic and metamorphic clasts predominate and matrix is arkosic. Deposits 0.5–8.0 m thick are exposed beneath terraces 14–20 m above present channels graded to the Rio Grande. Exposures are extensive near Rio Chiquito and south to Bland Canyon. Overlies Cochiti Formation or Otowi Member of the Bandelier Tuff. Soils generally thin (<1 m) and moderately developed having local Stage III carbonate morphology and buried Bt horizons

Qp₃ Piedmont alluvial deposit 3 (middle Pleistocene)—Poorly sorted cobble to boulder gravel and sand. West of the Rio Grande, clasts are predominantly andesite and silicic tuff derived from the west and the matrix is rich in lithic fragments and quartz. East of the Rio Grande granitic and metamorphic clasts predominate and matrix is arkosic. Overlies Cochiti Formation, Otowi Member of the Bandelier Tuff, or Santa Fe Group deposits. Extensive exposures are preserved north of Bland Canyon. Soils are 0.5–1.0 m thick with Stage II or Stage III carbonate morphology; strongly developed Bt horizons locally are buried by El Cajete tephra. Deposits 0.5–8.0 m thick are exposed beneath terraces 25–40 m above present channels graded to the Rio Grande

Qp₂ Piedmont alluvium (middle? Pleistocene)—Poorly sorted cobble to boulder gravel and massive sand and local silt beds in the southeast part of the map area beneath terrace remnants 45–60 m above present channels. West of the Rio Grande, clasts are predominantly andesite and silicic tuff derived from sources in the Jemez Mountains west of the map area and the matrix is rich in lithic fragments and quartz. East of the Rio Grande, clasts are mainly granitic and metamorphic clasts and matrix is arkosic. Overlies Cochiti Formation, lower Bandelier Tuff, or deposits of the Santa Fe Group. Extensive exposures west of Santa Cruz Arroyo are interfingered with middle(?) Pleistocene alluvial deposits (Qa₂) and include several carbonate horizons with Stage II or Stage III carbonate morphology and locally strongly developed buried Bt horizons

Qp₁ Piedmont alluvium (early? Pleistocene)—Poorly sorted cobble to boulder gravel forming terrace remnants >60 m above present channels. Clasts rich in andesite and silicic tuff derived from sources in the Jemez Mountains. Overlies Cochiti Formation or Otowi Member of the Bandelier Tuff. Near the Town of Cochiti Lake, deposits overlie or grade laterally into deposits of unit Qa₁. Poorly exposed

Sheetwash deposits

Qsw Sheetwash deposits (Holocene and early Pleistocene)—Sand, fine sand, silt, and one or more buried soils capping mesas isolated from major arroyos. Locally includes eolian deposits, some reworked. Most deposits include primary and reworked El Cajete tephra and admixed basaltic colluvium. Overlies basalt and andesite flows or older alluvial deposits. Overlain by eroded late Pleistocene or Holocene fluvial and eolian deposits. Soils within unit are 1.0 to > 2.0 m thick and contain buried Bt horizons and local Stage IV carbonate morphology and are locally brecciated. Thickness 2–8 m

Colluvial deposits

- Qc Colluvium (Holocene to middle Pleistocene)**—Rockfall, debris-flow, and poorly sorted alluvial deposits at the base of cliffs, particularly along White Rock Canyon and major tributaries such as Capulin Canyon. Texture and clast lithology is variable. Deposits include ~55 ka El Cajete tephra in many areas. Overlies Bandelier Tuff in the northwest part of map area and volcanic rocks and landslides elsewhere. Northwest of the Pajarito fault zone, Goff and others (1990) showed colluvial deposits "...only where extensive or where covering critical contacts." Surface soils are thin (<0.5 m) and weakly developed at most locations, but lenses of El Cajete tephra, buried soils with strong Bt horizons (west of the Rio Grande) or K-horizons (in White Rock Canyon) demonstrate that many deposits are locally older than late Pleistocene. Thickness generally 4–10 m, but locally exceeds 25 m along White Rock Canyon
- Qls Landslide deposit (Holocene to early Pleistocene)**—Massive gravity slide deposits mantled by basaltic colluvium, mainly exposed along the steep walls of White Rock Canyon, along the La Bajada fault scarp and in the Jemez Mountains. Deposits consist of slump blocks with coherent internal stratigraphy near canyon rims and progressively deformed slumps and debris flows closer to the Rio Grande. Stratigraphic dips in the slump blocks range from 10° to 30° toward head scarps. Failures mainly occurred along steeply dipping planes rooted in the Santa Fe Group, and in hydromagmatic deposits and other altered volcanic rock. Slide material overlies rocks of the Santa Fe Group at most sites. Deposit morphology and inclusion of upper Bandelier Tuff in some deposits suggests that slides were active in early Pleistocene time, but that many stabilized in middle to late Pleistocene time. Carbonate morphology is Stage IV at some sites, and Stage III carbonate morphology and buried Btk horizons are present in most exposures. Soils are generally 0.8 to 1.4 m thick. Most slides are inactive, but lake drawdown after high levels in the mid-1980s reactivated several major slides along the western margin of Cochiti Lake. El Cajete tephra (~55 ka) overlies landslide deposits near Cochiti Lake and along the La Bajada escarpment

SEDIMENTARY ROCKS AND DEPOSITS

Santa Fe Group and deposits

- QTc Cochiti Formation (lower Pleistocene to Miocene)**—Weakly lithified pebble to cobble gravel, massive to planar-bedded sand, thin (<0.3 m) beds of rhyolitic tephra and pumiceous alluvium, beds of fine sand and silt, and silt-rich debris flows containing volcanic clasts. Gravel fraction rich in andesitic and silicic rocks derived from west of the map area. The sand fraction is rich in lithic fragments and quartz. Includes older alluvium of Goff and others (1990) and Smith and others (1970). On both sides of the Rio Grande, between Sanchez Canyon and the Town of Cochiti Lake, upper 2–10 m of the Cochiti Formation consists of dark-colored sand containing beds and concentrations of pumice, some of it tubular and nearly aphyric, correlated with the ~1.8 Ma San Diego Canyon ignimbrite (Spell and others, 1990; Smith and Kuhle, 1998). Interbedded with unit Tsfa south of the Town of Cochiti Lake and near the intersection of Cochiti and Bland Canyons. Underlies lower Bandelier Tuff or piedmont alluvium. Dips gently northeast near the Town of Cochiti Lake, more steeply (>10°) near faults. Northwest of the

Pajarito fault zone, Cochiti Formation of Goff and others (1990) is a black to gray volcanoclastic unit consisting of debris flows, local zones of fluvial sediments and andesitic cinder cone debris, and flows of andesite too thin to show at map scale, interbedded with volcanic rocks of the Keres Group (Gardner, 1985; Gardner and others, 1986; Smith and others, 2001). Thick deposits tend to be covered by colluvium, estimated maximum thickness >30 m, base not exposed

QTsfa Santa Fe Group, axial channel facies (lower Pleistocene and Pliocene)—Slightly lithified pebble to cobble gravel rich in rounded clasts, arkosic sand, and thin beds of silty sand. Coarse units are 0.5–3.0 m thick, massive to cross-bedded, and locally planar-bedded. Gravel generally >70 percent quartzite, granite and other resistant rocks from northern New Mexico; andesitic and dacitic rocks from the Jemez Mountains common locally; vesicular basalt uncommon. Matrix quartzose or arkosic. Along White Rock Canyon, locally includes areas of pink silty sandstone that may correlate with the middle Santa Fe Group. Maximum thickness along Cañada de Cochiti; extensive exposures near Medio Canyon and in the southern part of the quadrangle on both sides of the Rio Grande. Fills channels in and locally interbedded with Cochiti Formation (QTc). Lies beneath landslide deposits, Pliocene basalt, or hydromagmatic deposits at most exposures. Paleocurrent direction measured on channels, gravelly crossbeds, and imbricated cobbles range from 140°–230°, and averages about 180°. Mainly undeformed except near faults. Near the mouth of Medio Canyon interlayered with a basaltic flow dated at about 2.5 Ma (Bachman and Mehnert, 1978). Thickness 5 to >70 m

Tsf Undivided Santa Fe Group (Pliocene to upper Miocene)—White, tan and pink, moderately lithified, planar-bedded to massive silty sandstone, siltstone, and cross-bedded pebbly sand in sparse channels. Sandstone beds up to 4 m thick; channels <1 m. Coarse units locally cemented with sparry calcite. Clasts mainly: (1) intermediate volcanic rocks and quartzite from southern Colorado and the northern Sangre de Cristo Range, and (2) Precambrian granite and associated rocks from the southern Sangre de Cristo Range. Matrix arkosic. Locally beneath tuffs of Canovas Canyon (Tkct) and unconformably overlies Galisteo Formation (Tgs) in the northwestern map area. Dips gently (<8°) to the west and northwest. Correlates, in part, with the Tesuque Formation of Galusha and Blick (1971), and the Ancha Formation of Spiegel and Baldwin (1963). Thickness >100 m

Pre-Santa Fe Group sedimentary deposits

Tgs Galisteo Formation (Eocene)—Tan and pink to brownish red beds of well-indurated sandstone, siltstone, arkose, and conglomerate; conglomerate beds locally contain limestone, chert, and granitic fragments from pebble to boulder size eroded from Paleozoic and Precambrian rocks. Exposed on rotated fault block with beds dipping steeply west in northwest part of map area. Unconformably underlies Santa Fe Group; base of unit not exposed; maximum observed thickness about 200 m

VOLCANIC ROCKS AND DEPOSITS

Tewa Group

The Pajarito Plateau area of the southeastern Jemez Mountains (fig. 1) is underlain by the Otowi (Qbo) and Tshirege (Qbt) Members of the Pleistocene Bandelier Tuff, erupted during collapse of the Valles caldera. These tuffs were deposited unconformably on underlying basaltic volcanic rocks of the Cerros del Rio volcanic field and on precaldera volcanic rocks of the Keres Group. Postcaldera volcanic deposits in the La Bajada constriction area are limited to reworked pumice and ash deposits of the approximately 55 ka El Cajete tephra (Reneau and others, 1996; Wolf and others, 1996). This pumice and ash blanket the northeastern slopes of eroded volcanic highlands east of the Rio Grande.

- Qec **El Cajete tephra (late Pleistocene)**—White to gray, poorly sorted rhyolitic pumice fall deposits; pumice clasts contain sparse phenocrysts of quartz, sanidine, biotite, and clinopyroxene. Most exposures have been reworked and concentrated by fluvial or slope processes. Overlies buried soil containing a well-developed Bt horizon invaded by carbonate. Derived from the El Cajete vent in the Valles Caldera (fig. 1); age ~50 to 60 ka (Reneau and others, 1996). Exposed in local, dune-like outcrops as thick as 8 m

Bandelier Tuff

- Qbt **Tshirege Member of Bandelier Tuff (early Pleistocene)**—White to pink slightly welded pyroclastic flows and a thin (< 0.5 m) pumiceous fall unit, both of rhyolitic composition and containing abundant phenocrysts of chatoyant sanidine and quartz and trace clinopyroxene, hypersthene, and fayalite. Consists of two to five pyroclastic flows separated by pumice concentrations or thin, sorted partings, exposed along deep canyons west of the Rio Grande; thinner (<25 m) flow sections are preserved locally in shallow canyons east of the Rio Grande. Thickness generally <60 m, but locally >90 m along Medio Canyon. Paleoflow directions to the southeast. Overlies lower Bandelier Tuff or pumiceous piedmont alluvium of the Toledo interval. Derived from the Valles caldera area northwest of the map area. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 1.22 ± 0.02 Ma (Izett and Obradovich, 1994)
- Qbo **Otowi Member of Bandelier Tuff (early Pleistocene)**—White to pink, nonwelded rhyolitic ash-flow tuff and a laminated to poorly sorted compound pumiceous fall unit as thick as 10 m, both containing abundant phenocrysts of chatoyant sanidine, quartz and sparse mafic phenocrysts. The Otowi Member consists of one to three thick ash-flow units comprising a compound-cooling unit as thick as 30 m. Lithic fragments generally are more abundant than in unit Qbt. Best exposed south of Capulin Canyon and southwest of the Town of Cochiti Lake. Overlies 2 to 5 m of gray pumiceous alluvium (upper Cochiti Formation) in areas southwest of Lummis Canyon. Locally overlies axial gravel deposits (Qa₁). Overlain by upper Bandelier Tuff, and andesitic flows. Derived from the Valles caldera northwest of the map area. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 1.61 ± 0.01 Ma (Izett and Obradovich, 1994)

LAVA FLOWS AND RELATED DEPOSITS OF THE CERROS DEL RIO VOLCANIC FIELD

The Cerros del Rio volcanic field is a predominantly basaltic to andesitic volcanic plateau along the southeast flank of the Jemez Mountains (fig. 1) of northern New Mexico. Lavas and related pyroclastic deposits of this field are locally exposed over 700 km² and reflect eruption of at least 120 km³ of rift-related mafic magma, mainly between 2.7 and 1.1 Ma. Most of the lava flows are of Pliocene and early Pleistocene age and predate large-volume silicic caldera eruptions in the nearby Jemez Volcanic Field; however, late-stage eruptions from the Cerros del Rio volcanic field post-date eruption of the Tshirege Member (1.2 Ma; Valles Caldera) of the Bandelier Tuff in the Jemez volcanic field. Most of the eruptive centers in the Cerros del Rio volcanic field are central-vent volcanoes ranging from low-relief shield centers to remnants of steep-sided, breached cinder cones. These lavas have from 49 to 64 weight percent SiO₂ and exhibit a strong correlation between landform and whole-rock chemistry. The low-silica, subalkaline basaltic lavas erupted from broad shield volcanoes and formed thin (< 3–4 m) low-viscosity flows that traveled far; conversely transitional to mildly alkaline basalts and basaltic andesites formed thick (as much as 30 m) discontinuous lavas flows that erupted from high-relief, steep-sided, dissected vents. Dacitic lavas are related to late-stage dome growth and eruption of thick (as much as 50 m), even more viscous blocky lava flows that issued from one well-defined vent area at Tetilla Peak about 2 km south of the map area (Sawyer and others, 2002) and locally in tributary canyons of the Rio Grande, west of the map area.

Volcanic deposits of the Cerros del Rio volcanic field are divided into a three-fold classification representing early (1), middle (2), and late (3) phases of eruption that persisted from about 2.7 Ma to 1.1 Ma. Volcanic units in the map area are believed to represent products of monogenetic eruptive centers of the early (>2.7–2.59 Ma), middle (2.59–2.1 Ma), and late (1.5–1.1 Ma) volcanic phases of Thompson and others (2006). These subdivisions are based on 1:24,000-scale geologic mapping, stratigraphic studies, ⁴⁰Ar/³⁹Ar geochronology, and paleomagnetic and aeromagnetic data. Some geochemical data were used to identify rock lithologies within the stratigraphic subdivisions for the entire field and were incorporated in unit descriptions, where available, for volcanic deposits in the map area. Volcanic rock names are based on the standard IUGS classification scheme (Le Bas and Streckeis, 1991), however, only root names are used in map unit description. Some volcanic units contain rocks of variable composition, spanning classification boundaries. In these cases, the dominant rock type was used for the unit name and ranges of compositions are presented in table 1. Preliminary results of new ⁴⁰Ar/³⁹Ar age determinations are presented in unit descriptions. Locations for samples referenced in the text are presented in table 2. In places, map units represent the consolidation of deposits of limited extent and are based on similar lithologic character, stratigraphic position, inferred age, aeromagnetic and paleomagnetic signatures, and aerial extent of similar or related deposits. Map-unit nomenclature for the volcanic deposits in part reflects that proposed by Aubele (1978, 1979).

Colors of the lava flows and cinder deposits used in unit descriptions were determined by comparison with a Munsell color chart (Munsell Color, 1995).

Andesite of Little Cochiti cone (early Pleistocene)—Reddish brown to medium gray andesite (58–60 weight percent SiO₂) lava flows (Qlc) and associated pyroclastic deposits (Qlcc) erupted from small volcanic cone in the southeastern part of the map area herein referred to as Little Cochiti cone. Little Cochiti cone deposits post-date down-to-west offset along the La Bajada fault, whose footwall formed a topographic escarpment over which westward flowing lava cascaded toward the present day course of the Rio Grande. Subsequent down-to-west offset along the La Bajada fault may have accentuated the offset of deposits preserved on the hanging wall and footwall blocks. Basal lava flows are typically thin (3–5 m), platy and discontinuous. Sparse phenocrysts include olivine, pyroxene and plagioclase in decreasing order of abundance, xenocrysts of plagioclase and lesser quartz are common near the vent area centered about hill 6598' on the Caja del Rio. Maximum exposed thickness is 70 m

Qlcc **Cinder deposits**—Near-vent pyroclastic deposits, predominantly scoria and spatter agglutinate and minor flow material, present only in proximity to eroded vent area

Qlc **Lava flows**—Medium to dark gray andesite lava flows; typically thin (3–5 m), platy and discontinuous and are everywhere overlain by near-vent deposits, predominantly cinder and lesser amounts of spatter. An ⁴⁰Ar/³⁹Ar isotopic age of 1.14±0.13 Ma was obtained from a lava flow near the head of Santa Cruz Arroyo (sample 96TCD08). Lava flows have reversed aeromagnetic signature and reverse magnetic polarity based on magnetic fluxgate determinations

Qd **Dacite of Arroyo Montoso (early Pleistocene)**—Dark gray to black, fine grained to glassy, aphyric dacite lava flows and dome remnants (64–65 weight percent SiO₂) best exposed near the confluence of the Rio Grande and Arroyo Montoso. Lava flows are thick (up to 20 m) and massive with brecciated flow bases and flow foliated tops. Sparse phenocrysts of olivine ± pyroxene ± plagioclase occur locally in a microcrystalline to cryptocrystalline groundmass. Partially resorbed xenocrysts of plagioclase ± quartz are sparse but ubiquitous. An ⁴⁰Ar/³⁹Ar isotopic age of 1.31±0.08 Ma was obtained from a lava flow above the Rio Grande (sample DN85113). Locally overlies deposits of unit Qbo. Maximum exposed thickness is 170 m

Andesite of Cochiti volcano (early Pleistocene)—Reddish brown to medium gray lava flows and oxidized cinder and spatter erupted from Cochiti volcano near the southwestern boundary of the map area. Cochiti volcano deposits post-date down-to-west offset along the Cochiti fault, whose footwall scarp formed a topographic barrier to eastward deposition of lava flows. Consists of an upper (Qcu) and lower (Qcl) sequence of preserved lava flows and near vent pyroclastic material (Qcuc) associated with the upper unit. Vent area for upper unit is coincident with eroded, conical summit of Cochiti volcano in on the eastern margin of the map area. Maximum exposed thickness is 350 m

- Qcuc **Upper unit, cinder deposits**—Near-vent pyroclastic deposits, predominantly scoria and spatter agglutinate and minor flow material. Deposits are only present along the eastern edge of the map area
- Qcu **Upper unit, lava flows**—Medium to dark gray andesite lava flows (59–62 weight percent SiO₂); typically thin (3–5 m), platy and discontinuous and are everywhere overlain by near-vent deposits, predominantly cinder and lesser amounts of spatter. Sparse phenocrysts include olivine, pyroxene and plagioclase in decreasing order of abundance. An ⁴⁰Ar/³⁹Ar isotopic age of 1.51±0.05 Ma was obtained from a lava flow near the base of the section on the northwest side of Cochiti volcano (sample 3MRG3). These flows have reverse aeromagnetic and paleomagnetic signature
- Qcl **Lower unit**—Medium to dark gray andesite lava flows (53–59 weight percent SiO₂) containing sparse phenocrysts include olivine, pyroxene and plagioclase in decreasing order of abundance; slightly higher proportions of olivine than in unit Qcu. Flows are interpreted to have reversed magnetic polarity based on aeromagnetic signature. Poorly exposed, maximum thickness 40 m, base not exposed
- Qac **Basaltic andesite of Cochiti Lake (early Pleistocene)**—Medium- to dark-gray, basaltic andesite (54 weight percent SiO₂) lava flows, typically 2–4 meters thick exposed along the Rio Grande near the southern edge of the map area. Sparsely phyric containing phenocrysts of olivine±pyroxene. An ⁴⁰Ar/³⁹Ar isotopic age of 2.52±0.04 Ma (sample DN9612) was obtained from a lava flow on the west bank of the Rio Grande southeast of the community of Cochiti Lake. Flows are interpreted to have reversed magnetic polarity based on aeromagnetic signature. Maximum thickness 25 m
- Qae **Basaltic andesite of Arroyo Eighteen (early Pleistocene)**—Medium-gray, massive basaltic andesite (55–57 weight percent SiO₂) lava flows (3–5m thick) containing sparse olivine ± pyroxene phenocrysts and abundant xenocrysts of plagioclase and quartz. Lava flows erupted from small cinder cones at the head of Arroyo Eighteen on the adjacent Montoso Peak quadrangle to the east. Erupted lavas flowed westward along a paleodrainage coincident with Arroyo Eighteen. An ⁴⁰Ar/³⁹Ar isotopic age of 2.56±0.02 Ma (sample 3MRG6) was obtained from a lava flow in a tributary to Arroyo Montoso near the eastern edge of the map area. Reverse polarity based on paleomagnetic determination and aeromagnetic signature. Maximum exposed thickness is 65 m but is locally thickened or repeated by down-to-west normal faults
- Tb **Basalt of La Bajada rim (Pliocene)**—Medium- to dark-gray basaltic (48–50 weight percent SiO₂) lava flows exposed principally along topographic rim of the La Bajada fault escarpment in the southeast part of the map area. Lava flows occur locally to the west of the escarpment in the hanging wall of the La Bajada fault. Includes both tholeiitic and transitional olivine basalts and locally basaltic andesites. Phenocrysts include olivine + pyroxene ± plagioclase and lesser iron-titanium oxides. Locally overlies paleochannel deposits of the Rio Grande. Likely erupted from

buried and (or) eroded volcanic centers overlain by units Qcu. Maximum exposed thickness is 40 m

- Tbc **Basalt of Cochiti Lake (Pliocene)**—Dark gray basalt lava flows (48–49 weight percent SiO₂) preserved as prominent benches west of the Rio Grande, northeast of the community of Cochiti Lake. Lava flows are typically 1.5 to 2 m thick, having massive interiors and vesicular, rubbly flow bases and tops and contain small (<1 mm) phenocrysts of olivine and pyroxene in a fine grained to microcrystalline groundmass. Locally contains xenoliths of rounded Precambrian pebbles, likely recycled from underlying Santa Fe Group sediments. Normal polarity based on magnetic fluxgate determinations. Maximum exposed thickness is 70 m
- Tca **Andesite of Colorado Peak (Pliocene)**—Andesitic lava flows grade transitionally into predominantly near-vent pyroclastic deposits near the summit and dissected southern flank of Colorado Peak, east of the map area on the Montoso Peak 7½-minute quadrangle. Most flows appear to have erupted from a central vent area characterized by a conspicuous summit crater and associated ring dikes and incipient flow breccias. Summit area is cut by northeast- and northwest-trending dikes. Dark-gray basaltic andesite to andesite (56–62 weight percent SiO₂) lava flows up to 15 m thick containing phenocrysts of olivine and pyroxene and abundant xenocrysts of resorbed plagioclase and sparse quartz. Lava flows are lobate in form and directed predominantly to the west and northwest but truncated and offset to the west by down-to-west Cochiti normal fault located on the Montoso Peak quadrangle. An ⁴⁰Ar/³⁹Ar isotopic age of 2.60±0.10 Ma was obtained from a lava flow near the summit of Colorado Peak east of the map area (sample 96TMP38). Normal magnetic polarity based on paleomagnetic and aeromagnetic signature. Maximum exposed thickness is 75 m, but exceeds 225 m to the east on the adjacent Montoso Peak quadrangle
- Tas **Andesite of Sanchez Canyon (Pliocene)**—Medium gray to reddish brown (56 weight percent SiO₂) andesite lava flows and associated near vent pyroclastic deposits exposed along the Rio Grande principally between Bland Canyon on the south and Capulin Canyon on the north. Locally includes oxidized andesitic scoria, breccia, spatter and spatter agglutinate interbedded with lava flows, particularly well preserved in the lower reaches of Bland Canyon where deposits may represent deeply dissected near vent deposits. Lava flows are discontinuous and variable in thickness from 1.5 to 10s of meters thick depending on local underlying paleotopography. Porphyritic lavas contain phenocrysts of olivine + pyroxene ± plagioclase in a fine-grained matrix. Locally, partially resorbed xenocrysts of plagioclase and quartz are present. Maximum thickness is 100 m
- Tcm **Andesite of Cerro Micho (Pliocene)**—Lava flows and associated near-vent deposits erupted from several eroded vent areas, the largest of which is preserved at Cerro Micho on the adjacent Montoso Peak quadrangle to the east. Thick lava flows up to 8–10 m, underlie the eastern rim of White Rock Canyon in the northwest part of the map area. Between White Rock Canyon and Arroyo Montoso, the section is exposed in several, down-to-west fault blocks. Scattered near-

vent deposits, predominantly cinders, overlie associated lava flows and are thickest along a northwest-southeast trending alignment of dissected cinder and spatter cones extending from the northwest corner of the map to Cerro Micho. Medium-gray to reddish brown andesite (57–60 weight percent SiO₂) lava flows. Although variable, most lava flows characteristically contain olivine and clinopyroxene phenocrysts, sparse to abundant plagioclase phenocrysts ± resorbed plagioclase xenocrysts in a fine-grained holocrystalline groundmass. Near-vent deposits at scattered localities along White Rock Canyon are reddish-brown pyroclastic deposits, predominantly scoria, spatter and lesser agglutinate. An ⁴⁰Ar/³⁹Ar isotopic age of 2.76±0.03 Ma (sample 3MRG5) was obtained from a lava flow in a tributary to Arroyo Montoso. Normal magnetic polarity based on paleomagnetic and aeromagnetic signature. Maximum exposed thickness is 300 m although thickness varies considerably and likely reflects eruption of lava flows onto an irregular paleotopographic surface

Ta Andesite and basaltic andesite, undivided (Pliocene)—Undifferentiated lava flows and some interbedded pyroclastic and (or) hydromagmatic deposits preserved in White Rock Canyon north of Arroyo Montoso. Deposits locally include andesite and basaltic andesite lava flows and associated breccias overlying hydromagmatic deposits of unit Tbm and underlying lava flows of unit Tcm. Maximum exposed thickness is 130 m

Tbm Hydromagmatic deposits (Pliocene)—Bedded to massive fall, surge, and flowage deposits composed of basaltic tuff and cinders, accidental fragments of the Santa Fe Group and thin (<10 m), interlayered basaltic flows. Thickest exposures are along Arroyo Montoso and along the Rio Grande south of Alamo Canyon. Ash-fall beds 0.3–3.0 m thick, composed mainly of ash and lapilli containing sparse bombs of accidental and basaltic fragments. Surge beds are planar and cross-bedded, locally rippled, coarse silt to pebbly sand, generally 0.1–0.4 m thick. Flowage deposits mainly matrix-rich pebble to boulder gravel in discontinuous beds 1 to 4 m thick. Near maars the frequency of accidental fragments decreases up-section. Locally sheared, slumped or brecciated. Thickness of fragmental flow deposits and interlayered basalt flows ~60 m along Arroyo Montoso (Self and others, 1996). Interlayered with Pliocene basalt flows and generally lies above Pliocene axial deposits of the Santa Fe Group. Lies beneath flows of basalt and andesite. Older than ~2.5 Ma; maximum age not closely constrained

VOLCANIC ROCKS AND DEPOSITS OF THE KERES GROUP

Keres Group (Miocene)—All precaldera volcanic and volcanoclastic deposits of the Pajarito Plateau area in the western part of the map area (units Tkpt, Tkbd, Tkhd, Tkha, Tkpa, Tka, Tkca, Tkoa, and Tkct) belong to the Keres Group as defined by Bailey and others (1969) and modified by Gardner and others (1986) and Smith and others (2001). The Keres Group rests unconformably on Santa Fe Group sediments and locally on 16-Ma basaltic lava flows (unit Tsfb) related to rifting (Goff and others, 1990). The Keres Group consists predominantly of andesite to dacite lavas, pyroclastic deposits, volcanic breccias, and sedimentary deposits (Gardner and others, 1986; Lavine and others, 1996). Age of the volcanic rocks ranges from

approximately 12 Ma near the base of the Paliza Canyon Formation to approximately 6.5 Ma, the youngest age reported for the Bearhead Rhyolite; most volcanism occurred between 10 and 8 Ma (Gardner and others, 1986; McIntosh and Quade, 1995; Lavine and others, 1996; Justet, 1999). Unit descriptions are modified from Goff and others (1990).

Paliza Canyon Formation

- Tkpt **Peralta Tuff Member of Bearhead Rhyolite**—White to tan, lithic-rich ash-fall tuff; pumice fragments contain phenocrysts of quartz, potassium feldspar, biotite+plagioclase; lithic fragments consist of volcanics from nearby sources. Tkpt fills in rugged volcanic topography on earlier Keres Group rocks; sources for all tuff units unknown; K-Ar age of lowermost tuff bed at Peralta Canyon type locality 6.81 ± 0.15 Ma; maximum observed thickness about 170 m
- Tkbd **Biotite dacite**—Domes, flows, and minor intrusive rocks of gray to pink porphyritic dacite containing phenocrysts of complexly zoned plagioclase and smaller phenocrysts of plagioclase, biotite, clinopyroxene, opaque minerals, \pm hornblende, \pm hypersthene, \pm quartz, \pm potassium feldspar; flows massive to sheeted; may contain flow breccia; K-Ar age of dome in upper Cochiti Canyon 8.8 ± 0.5 Ma; K-Ar age of dome in upper Bland Canyon 9.11 ± 0.19 Ma; maximum observed thickness about 150 m
- Tkhd **Hornblende dacite**—Domes, flows, and minor intrusive rocks of gray to pink porphyritic dacite containing phenocrysts of complexly zoned plagioclase and smaller phenocrysts of plagioclase, hornblende, clinopyroxene, opaque minerals, \pm biotite, \pm hypersthene, \pm apatite, \pm potassium feldspar; flows massive to sheeted; may contain flow breccia. K-Ar age of dome at head of Sanchez Canyon 9.5 ± 2.5 Ma; K-Ar age of dome on southeast slope of Boundary Peak 9.48 ± 0.44 Ma; maximum observed thickness about 60 m
- Tkha **Hornblende andesite**—Black to gray to pink domes and flows of glassy to devitrified andesite having small phenocrysts of plagioclase, clinopyroxene, oxidized hornblende \pm hypersthene \pm rare biotite; may display flow banding or contain flow breccia; ages of various flows unknown; maximum observed thickness about 45 m
- Tkpa **Porphyritic andesite**—Gray to black domes and flows of coarse porphyritic andesite having large phenocrysts of plagioclase and abundant phenocrysts of clinopyroxene and hypersthene; flows may be sheeted or contain flow breccia; K-Ar age of flow at summit of St. Peters Dome 8.69 ± 0.38 Ma; K-Ar age of dome west of Rancho Canada 9.33 ± 0.19 Ma; maximum observed thickness about 150 m
- Tka **Undivided andesite**—Gray to pink to black flows, domes, and minor intrusives of porphyritic andesite containing phenocrysts of plagioclase, clinopyroxene, and hypersthene; flows massive to sheeted; may contain flow breccia; displays pervasive hydrothermal alteration in canyon bottoms; ages of various flows unknown; maximum observed thickness about 50 m

- Tkca **Clotted andesite**—Gray to black flows of porphyritic andesite having abundant distinctive plagioclase-pyroxene clots 2 mm in diameter and phenocrysts of plagioclase, clinopyroxene, and hypersthene; flows massive, rarely sheeted or brecciated; ages of flows unknown; maximum observed thickness about 50 m
- Tkoa **Olivine andesite**—Black to gray domes and flows and minor red cinder deposits of plagioclase, clinopyroxene, hypersthene and iddingsitized olivine; flows massive with vesicular flow tops; flows rarely sheeted; ages of various flows unknown; maximum observed thickness about 210 m
- Tkct **Canovas Canyon Rhyolite**—White to pink ash-fall and ash-flow tuffs best preserved in laharic deposits of the Cochiti Formation; "pink tuff" apparently underlies all other Keres Group volcanic rocks and overlies Santa Fe Group on south and east flanks of St. Peters Dome; estimated age range of unit 9.0–13.0 Ma; maximum observed thickness about 20 m
- Basalt flows in Santa Fe Group
- Tsfb **Basalt flows in Santa Fe Group (Miocene)**—Thin discontinuous flows, pillow basalt and palagonite tuff composed of black alkali basalt and basanite containing small phenocrysts of olivine ± clinopyroxene ± plagioclase; vesicles commonly filled with calcite; olivine may be altered to iddingsite; basalts occur in upper exposures of Santa Fe Group on lower south and east flanks of St. Peters Dome (Frijoles 7½-minute quadrangle); one small intrusive plug of alkali basalt in Galisteo Formation is correlated with this unit; K-Ar age of thin flow in upper Medio Canyon 16.5±1.4 Ma. Maximum observed thickness about 5 m

EXPLANATION

Contact

Normal fault—Dashed where inferred from aerial photographs, dotted where concealed; bar and ball on apparent downthrown side

Lineament—Located using aerial photographs and reduced to pole aeromagnetic map; coincides with zones of minor fracturing and faulting

Lava flow direction—Inferred lava flow direction for select volcanic rock units Dike

Inclined bedding—Showing strike and dip

Sample location—With sample number

Base from U.S. Geological Survey Cochiti Dam, New Mex., 1953, revised 1993

North American Datum of 1927 (NAD 27)

Projection and 10,000-foot ticks: Universal Transverse Mercator

New Mexico coordinate system, central zone

1,000-meter ticks, Universal Transverse Mercator, zone 13

Scale 1:24,000

The geology was mapped from 1997–1999 and modified in 2004–2008. The primary mapping responsibilities were as follows: Dethier mapped the surficial deposits, basin-fill sedimentary deposits, Miocene to Quaternary volcanic deposits of the Jemez volcanic field, and a preliminary

version of fault distribution. Thompson and Hudson mapped the Pliocene and Quaternary volcanic deposits of the Cerros del Rio volcanic field. Thompson, Minor and Hudson mapped surface exposures of faults and Hudson conducted paleomagnetic studies for stratigraphic correlations. Thompson prepared the digital compilation of the geologic map.